Vacuum 113 (2015) 59–63

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Charging effects of plasma impact on microconductor structures on an insulator in plasma processing technologies

V.P. Tarakanov [a, c], E.G. Shustin [b, c, *]

[a] Joint Institute of High Temperatures of RAS, Moscow, Russia
[b] V.A. Kotelnikov Institute of Radio Engineering and Electronics of RAS, Fryazino Branch, Fryazino, Russia
[c] National Research Nuclear University MEPhI, Moscow, Russia

ARTICLE INFO

Article history:
Received 1 November 2014
Received in revised form
15 December 2014
Accepted 16 December 2014
Available online 24 December 2014

Keywords:
Plasma processing reactors
Computer simulation
Ion etching
Charging

ABSTRACT

When creating nanoelectronic devices conventional plasma technologies are faced with the increasing role of the charge accumulation on the treated surfaces. In this paper we present the results of computer simulation of the effect of charge accumulation on features of plasma action to structure “a conductor on an insulator”. The simulation was carried out using the KARAT code, applying a mathematical model based on Maxwell equations with the various material equations. An important feature of the model is that the transverse dimension of the conductor is much smaller than the Debye radius of the surrounding plasma.

Calculations have shown that the ion beam appears to be not only strongly non-uniform over the cathode width (the beam width occupies 0.2 of the cathode width), but also is spread over a large range of arrival angles on the cathode. Although in this work qualitative results are presented from calculations based on conditional parameters of the system, the model allows quantitative simulation of an actual practical situation in the plasma reactor, including pulse modulation of plasma parameters.

1. Introduction

Plasma technologies for surface treatment of materials (etching, thin film deposition, implantation and modification of the structure and composition of the surface layer) are fundamental for modern solid state electronics. With diminishing characteristic dimensions of elements of integrated circuits, as well as with development and study of structures of nanoelectronics based on new principles, etching processes should be controlled at the nanometre scale.

However, when creating nanoelectronic devices conventional plasma technologies are faced with the inevitable problems including increasing role of the accumulation of a charge on the treated surface [1]. Understanding the effect of surface charging on the process of plasma action and the resulting topology of structures on the nanometre scale is a key to achieving this level of control.

There are two physical effects caused by charge accumulation on the dielectric and having significant impact on the results of plasma processes in nanoelectronics. Firstly, the electric field in the dielectric, for example, in the oxide film of a transistor gate leads to gain of a current through the insulator, and even to breakdown of the dielectric layer [2]. Secondly, in the process in which the plasma acts on the heterogeneous surface areas (etching and deposition through the mask, exposure to metallic or semiconducting properties on the insulating substrate, and the like) electric fields at the surface distort trajectories of ions impacting on the treated structure and as a result, can lead to distortion of the structure topology.

Numerical simulation provides an important method for studying the complex processes that occur during both plasma patterning of microelectronic structures and plasma enhanced deposition of elements for the structures.

Local surface charging caused by the directionality difference between isotropic electron and anisotropic ion fluxes was analysed by computer simulation for the first time in Ref. [3]. Subsequently more and more complex and accurate models for analysis of the effects of charging the dielectric during plasma etching were developed [4–10]. Simultaneously, experimental studies were conducted and practical solutions developed to overcome the problems [see, for example, 11–13].

* Corresponding author. V.A. Kotelnikov Institute of Radio Engineering and Electronics of RAS, Fryazino Branch, Fryazino, Russia. Tel.: +7 496 5652569.
E-mail address: shustin@ms.ire.rssi.ru (E.G. Shustin).

http://dx.doi.org/10.1016/j.vacuum.2014.12.014
0042-207X/

In Refs. [3–13] problems were studied that were associated with the impact of the plasma on structures consisting of layers of different etching rate, but not different significantly in their electrical conductivity. In this case the effect of the charge accumulation is determined by electric fields in the inhomogeneous geometry of surfaces and is particularly strong at etching grooves, or holes, with a high aspect ratio. However, perhaps no less important task for plasma technologies is etching structures such as “conductor on the insulator.” This problem occurs when one creates the connecting conductors to the active elements, as well as patterning nanoscale structures, including two-dimensional structures, at metals and semimetals. Although in practice this problem is currently faced often enough and is solved usually by quite complex empirical methods [14,15], the problem, as far as we know, has not been analysed by theoretical methods.

In this paper we present the results of computer simulation of the effect of charging a structure of the “conductor on the insulator” type. The model makes it possible to observe how the spatial and energy distributions of the ions bombarding the conductor are transformed with the accumulation of charge on the surrounding dielectric, for a DC potential on the conductor and for pulsing the potential on the conductor. An important feature of the model is that the transverse dimension of the conductor is much smaller than the Debye radius of the surrounding plasma, resulting in the observed effects to fully determine the impact of the ion flow from the plasma to the processes on the surface of the conductor and on the nearby dielectric.

2. The model

The simulation was carried out using the KARAT code [16]. The mathematical model underlying the code is based on the Maxwell's equations with also the various material equations, including one in the form of the kinetic equation solved by the PiC (Particle in the Cell) method and also in the form of various phenomenological models. The Maxwell's equations are solved by an explicit finite difference scheme with overstepping on the rectangular shearing grid with second order of accuracy. Such a method of solution imposes certain restrictions on the steps in time and space:

$$\Delta t < \frac{\Delta x}{c}, \frac{1}{\omega_p}, \frac{1}{\nu}, \frac{1}{\omega_c}, \quad \Delta x < l, rc, \lambda_D$$

where Δx is the step on a coordinate, Δt is the time step, c is the light velocity, l is the specific minimal size, ω_p is the electron plasma frequency, λ_D is the Debye radius, ω_c is the electron cyclotron frequency, r_c is the Larmour radius, ν is the electron collision frequency.

In this work the two-dimensional XZ plane version is applied in which all components of the particle velocities and electromagnetic fields are considered. Plasma is modeled in the frame of the PiC method. In the plane a homogeneous current-free (at the initial moment) plasma is set up with parameters common to low pressure plasma processing reactors such as RIE reactors, and also ones with electron beam excited plasma: density of electrons 10^{10} cm^{-3}, electron temperature 4 eV and immobile ions ($T_i = 0$). At the characteristic pressures of the neutral gas (10^{-4}–10^{-2} Torr) for such reactors, the mean free paths of both ions and electrons considerably exceed the characteristic width of a plasma sheath, therefore plasma in the model is considered as completely ionized and collisionless. The time step for particles of bigger mass is increased automatically, so that their displacement and impulse increments don't become less than the accuracy of representation of the floating point format in the computer. The calculation area (see Fig. 1) is a rectangle of 1 mm in length and 0.5 mm in width. Its lateral and bottom borders are at zero potential. The top border is covered with a dielectric layer of 0.01 mm in thickness with dielectric permittivity ε_r. The dielectric layer is charged by the PiC

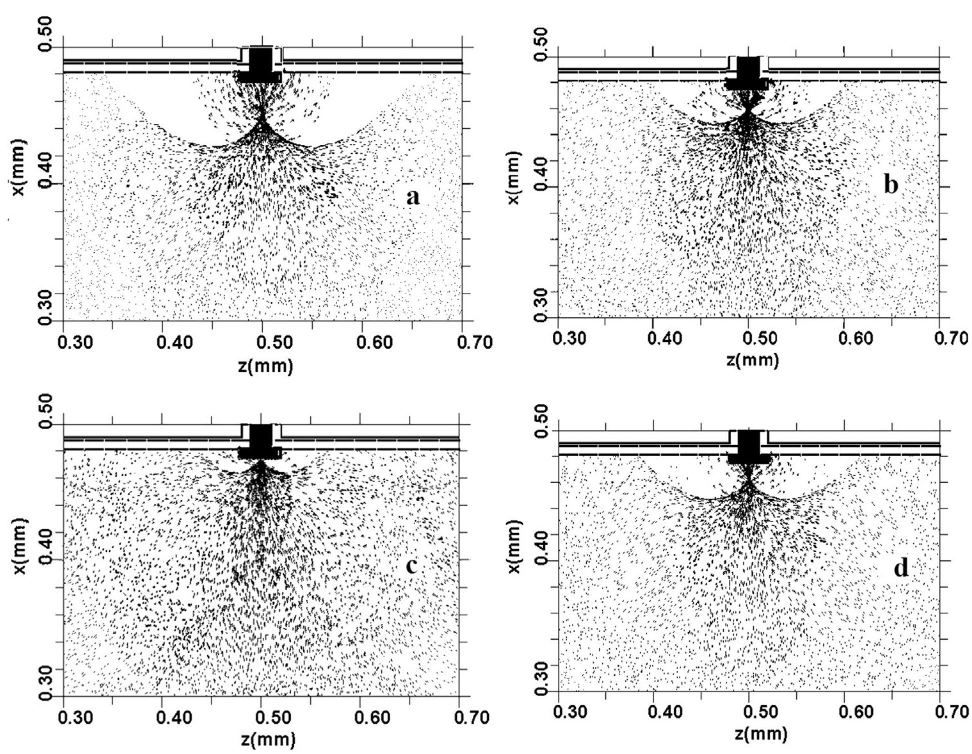

Fig. 1. Distributions of ions, $M_i = M_H$, in the field near the negatively charged electrode at the moments (a) $t = 10$ ns (b) $t = 20$ ns (c) $t = 40$ ns (d) the same for $M_i = 10\ M_H$ at $t = 40$ ns.